ASSESSMENT OF THE IMPACT OF OPERATIONAL PARAMETERS ON THE EFFICIENCY OF REVERSE OSMOSIS SYSTEMS

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Abstract

This paper addresses the pressing issue of water quality assurance under increasing anthropogenic pressure. The efficiency of reverse osmosis (RO) technology for water purification, particularly in the pharmaceutical industry, is analyzed. Data concerning the impact of key operational parameters (pressure, recovery rate) and physico-chemical characteristics of feedwater (pH, hardness, alkalinity) on membrane purification efficiency are systematized. Particular attention is given to the problems of membrane scaling, especially in regions with high concentrations of hardness salts. Methods for assessing water's scaling tendency (LSI, SDI indices), monitoring strategies, and water pre-conditioning, including antiscalant dosing (phosphonates, polyacrylic acid) and pH adjustment, are examined. Modern approaches to optimizing RO systems, such as the use of digital twins and hybrid technologies (RO-UV, RO-ED), which contribute to improved purification quality, energy efficiency, and reduced fouling risks, are also highlighted. Recommendations are proposed for optimizing operational parameters, developing water stability assessment methodologies, and implementing monitoring systems to ensure the long-term efficiency of reverse osmosis systems.

Key words: reverse osmosis, water purification, membrane fouling, scaling, lsi index, sdi index, antiscalants, operational parameters, water quality monitoring.

In modern conditions, water pollution and the preservation of its quality are becoming particularly relevant. Anthropogenic impact, industrialization, and climate change are deteriorating the quality of natural water supply sources, necessitating the implementation of effective purification technologies. This is especially important in industries with high water quality requirements, particularly in pharmaceuticals, where it is used as a raw material, solvent, and for equipment washing.

One of the most effective technologies is reverse osmosis (RO), which ensures over 99% removal of impurities, including hardness salts and heavy metals [1]. However, the efficiency of RO systems largely depends on the quality of the feed water. Parameters such as pH, alkalinity, hardness, temperature, and recovery rate affect membrane fouling, reducing productivity, selectivity, and membrane lifespan [2].

Particular attention is required for the purification of low-mineralized, industrial, and drinking waters in regions with elevated concentrations of hardness salts (Ca^{2+}, Mg^{2+}), high alkalinity, and pH.

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Such conditions are characteristic of the southern and eastern regions of Ukraine and cause scaling, which reduces filtration efficiency and requires frequent system maintenance [2].

The aim of this work is to systematize data on the influence of pressure, recovery rate, and physico-chemical characteristics of water on the efficiency of membrane purification, with an emphasis on water softening, minimization of scaling, and ensuring the stable operation of RO systems.

High water hardness contributes to the formation of sediments on membrane surfaces, especially at high recovery rates. Concentration polarization is the primary prerequisite for scaling, which intensifies with increasing pressure [3].

The LSI (Langelier Saturation Index) and SDI (Silt Density Index) are commonly used to evaluate the scaling potential of water. A positive LSI value indicates water instability relative to carbonate sediments. SDI evaluates the presence of colloidal and suspended particles. Both indices are important during both the design and operation of systems [4].

Monitoring water characteristics at various stages (feed water, permeate, concentrate) allows for the timely detection of fouling. Important parameters are: pH, electrical conductivity, turbidity, TDS (Total Dissolved Solids), and ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, SiO_2 [5]. Automated analyzers provide continuous control and signal deviations [6].

Pre-conditioning includes dosing antiscalants, pH correction, and the use of ion-exchange softening. Reducing pH to 6,0 – 6,5 (e.g., with sulfuric acid) decreases the risk of carbonate scaling [7].

Antiscalants such as phosphonates (e.g., ATMP) and polymeric inhibitors (based on polyacrylic acid, PAA) effectively inhibit the crystallization of calcium salts [8, 9]. Phosphonates alter crystal morphology, and high molecular weight PAA better suppresses crystallization, although lighter fractions may cause biofouling.

Modern strategies for optimizing reverse osmosis (RO) systems increasingly include the application of digital models ("digital twins"), predictive algorithms, and hybrid technologies, such as combining RO with ultraviolet (UV) disinfection or electrodialysis (ED). These approaches improve the quality of water treatment, increase the energy efficiency of systems and reduce the risks of fouling.

The use of digital twins, which combine real sensor data with virtual system models, allows us to predict membrane behavior, optimize operating modes, and reduce maintenance costs. For example, at the desalination plant in Carlsbad (USA), the implementation of a digital twin resulted in a reduction of membrane maintenance costs by nearly $1,5 million over five years [10]. Furthermore, hybrid systems that integrate RO with other technologies demonstrate high efficiency in complex water treatment conditions. Studies have shown that such combinations allow for achieving a high degree of purification with reduced energy consumption and less concentrate formation [11].

Recommendations and prospects

1. Optimization of operational parameters: Further research is needed to determine optimal operating modes for RO systems under various feed water characteristics, particularly concerning pressure and recovery rate.

2. Development of water stability assessment methodologies: Implementing standard protocols that combine LSI, SDI, and other indicators will allow for more accurate prediction of scale formation and the adoption of appropriate measures.

3. Study of water softening efficiency: Comparative studies on the impact of different water softening methods, including ion-exchange and membrane technologies, will help determine the most effective strategies for specific conditions.

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4. Implementation of monitoring and control systems: The use of modern technologies, such as digital models and real-time monitoring systems, will contribute to increasing the efficiency and reliability of water purification systems.

Conclusions

The operational efficiency of reverse osmosis systems largely depends on the quality of the feed water and operational parameters. High hardness, pH, and other characteristics can lead to scale formation and reduced system productivity. The application of LSI, SDI, and other methods for assessing water stability, as well as the implementation of modern monitoring and control technologies, allows us to optimize the operation of water purification systems and ensure their long-term effectiveness.

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ЗАГАЛЬНА ОЦІНКА ВПЛИВУ ЕКСПЛУАТАЦІЙНИХ ПАРАМЕТРІВ НА ЕФЕКТИВНІСТЬ СИСТЕМ ЗВОРОТНОГО ОСМОСУ

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Анотація
У роботі розглядається актуальна проблема забезпечення якості води в умовах зростаючого антропогенного навантаження. Проаналізовано ефективність технології зворотного осмосу (RO) для очищення води. Систематизовано дані щодо впливу ключових експлуатаційних параметрів (тиск, ступінь відбору) та фізико-хімічних характеристик вихідної води (pH, жорсткість, лужність) на ефективність мембранного очищення. Особливу увагу приділено проблемам осадоутворення на мембранах, особливо в регіонах із високим вмістом солей жорсткості. Розглянуто методи оцінки схильності води до осадоутворення (індекси LSI, SDI), стратегії моніторингу та попереднього кондиціювання води, включаючи дозування антискалантів (фосфонати, поліакрилова кислота) та корекцію pH. Висвітлено сучасні підходи до оптимізації систем зворотного осмосу, такі як використання цифрових двійників та гібридних технологій (RO-UV, RO-ED), які сприяють покращенню якості очищення, енергоефективності та зменшенню ризиків забруднення. Запропоновано рекомендації щодо оптимізації експлуатаційних параметрів, розробки методик оцінки стабільності води та впровадження систем моніторингу для забезпечення довгострокової ефективності систем зворотного осмосу.

Ключові слова: зворотний осмос, очищення води, мембранне забруднення, осадоутворення, індекс LSI, індекс SDI, антискаланти, експлуатаційні параметри, моніторинг якості води.

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